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IN THIS ISSUE

News from the WOCE IPO

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Can this possibly be the end?

The last newsletter

Well here we are… This will the be last editorial for an International WOCE Newsletter and this issue should therefore be a bit special. It will look back over the 20 years of WOCE – from its first SSG meeting in Woods Hole in August 1983, to the final WOCE Conference in San Antonio in November this year…and beyond. For many of the readers of this newsletter, their research activities, their travel and their sea-going have been dominated for at least a decade by the demands of WOCE. I looked back and found that of the 28 SSG meetings, I have attended twenty, the earliest as an observer at SSG-2 in January 1984 (and I only missed one since SSG-9 in 1987). That's a lot of talk and a lot of travel and many of you have had a similar level of commitment.

Has all this investment made a difference and has it been worthwhile? Articles in this Newsletter will try to answer that question - from a science point of view by Carl Wunsch, the first SSG Chairman; from a data management standpoint; from the technology aspects and from a socio-economic Cost Benefit Analysis perspective.

I have concluded that WOCE scientists are a pretty camera-shy bunch because we discovered very few photographs taken at WOCE meetings. Maybe we only take photographs when we are having fun! We have found a few, however, that document WOCE from the very early stages right up to the last SSG in 2001. If any of you have more photographs we would be glad to scan them and put them in the WOCE archive.

Has WOCE changed the way we work as a scientific community?

I think so – firstly we wholeheartedly embraced electronic communication. The WOCE IPO established an electronic mail account as early as 1986 and the first WOCE web sites were set up in 1994 (the WWW originated at CERN in 1989 and by 1994 its use was growing at 1% per DAY! WOCE was a part of that rapid growth). One can easily argue that the level and speed of communication needed to plan an international programme as large and complex as WOCE and involving scientists on all continents would not have been possible a decade earlier when we would have had to use telephone, telex and fax plus letters. Those electronic means of communication never removed the need for people to meet.

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About WOCE

The World Ocean Circulation Experiment (WOCE) is a component of the World Climate Research Programme (WCRP), which was established by WMO and ICSU, and is carried out in association with IOC and SCOR.

WOCE is an unprecedented effort by scientists from more than 30 nations to study the large-scale circulation of the ocean. In addition to global observations furnished by satellites, conventional in-situ physical and chemical observations have been made in order to obtain a basic description of the physical properties and circulation of the global ocean during a limited period.

The field phase of the project lasted from 1990–1997 and is now being followed by Analysis, Interpretation, Modelling and Synthesis activities. This, the AIMS phase of WOCE, will continue to the end of 2002.

The information gathered during WOCE will provide the data necessary to make major improvements in the accuracy of numerical models of ocean circulation. As these models improve, they will enhance coupled models of the ocean/atmosphere circulation to better simulate – and perhaps ultimately predict – how the ocean and the atmosphere together cause global climate change over long periods.

WOCE is supporting regional experiments, the knowledge from which should improve circulation models, and it is exploring design criteria for long-term ocean observing system.

The scientific planning and development of WOCE is under the guidance of the Scientific Steering Group for WOCE, assisted by the WOCE International Project Office (WOCE IPO):

- W. John Gould, *Director*
- Peter M. Saunders, *Staff Scientist*
- N. Penny Holliday, *Project Scientist*
- Mike Sparrow, *Project Scientist*
- Jean C. Haynes, *Administrative Assistant*

For more information please visit:
http://www.woce.org

We did consider a video conference replacement for WOCE SSG-28 last November but decided it would not work. I imagine that 5 years from now the number of occasions on which the word WOCE is mentioned will not have diminished from its present level.

CLIVAR – the "New" programme.
And, looking to the future, we have the "New" programme CLIVAR. I put the word new in quotes because the first reference to CLIVAR in the WOCE Newsletter was back in 1994 when, following CLIVAR's second SSG meeting at Lamont (that I attended during a heat wave), Arnold Gordon wrote – *"CLIVAR will build on the effective infrastructure developed by WOCE and continue WOCE initiatives related to ocean variability, which is likely to include; upper ocean monitoring; repeat meridional flux sections; satellite altimetry; use of new technologies for ocean monitoring; use of chemical tracers to unravel the timescale of ocean circulation; and study of specific climate-related ocean phenomena and processes including inter-ocean fluxes and water mass formation processes".*

The latest CLIVAR Newsletter (CLIVAR Exchanges - www.clivar.org/publications/exchanges/index.htm) focuses on CLIVAR's activities in the Atlantic and has examples of all of those themes - so Arnold's prognosis is coming true.

Important news of the WOCE IPO. First I am very happy to announce that in Venice on Saturday October 7th Roberta Boscolo and her fiancée Emilio Marañon were married. Roberta now works for CLIVAR but you all know her as a past WOCE Newsletter editor. On page 18 is a photograph of Roberta and Emilio leaving the church – how else but by gondola.

Even more good news is that Penny Holliday and her husband Craig Harris are expecting their first child in January 2003. Congratulations to them both.

On a very sad note is the news reported on Page 3 of the untimely death of George Needler. It is a great shame that George will not be with us in San Antonio for our final WOCE celebration. George exerted a huge influence in the early stages of the project both contributing his scientific expertise and in establishing and directing the WOCE IPO. My personal recollections of George are happy ones of hours on the golf course both in Surrey and in Canada.

Countdown to December 31 2002. So, after the conference what remains to be done? The DVDs will be produced and distributed at the Conference and from the IPO, the production of the WOCE Atlases will continue with the first volume appearing in early 2003, the WOCE web site will continue as a link from the CLIVAR (www.CLIVAR.org) and WCRP (www.wmo.ch/web/wcrp/) sites. We will complete the WOCE IPO archive of documents and information and continue to operate the WOCE bibliography. The archive will be held here in Southampton by the UK National Oceanographic Library, but a record of its contents will be held by WCRP in Geneva.

And did we succeed? Only time will tell but there is a quote from Alan Longhurst that was published in the Oceanography Society Journal, Oceanography (Vol 13 (2) pp 3-4, June 2000). It forms the final paragraph of a letter by Alan in which he compares the planning and execution of big ocean programmes. Here's what he says:

"Finally our President challenges us to 'place the existing ideas presented here into perspective'. That's easy! Using the terms of classical perspective, I would place WOCE right in the foreground for its clarity in planning, efficiency of execution and the immediate value of its data to society. Back a bit, but not yet in the middle-distance, is JGOFS, more muddled as perhaps ecology must be but generating much new understanding about global carbon cycles which we shall need in a little while. In the middle-distance, perhaps because I know insufficient about it, I see GOOS glimmering out of the haze."

Praise indeed for WOCE from such an eminent biologist and a fitting note on which to say farewell.

George Treglohan Needler
(1935-2002)

Peter Koltermann, John Gould and Allyn Clarke

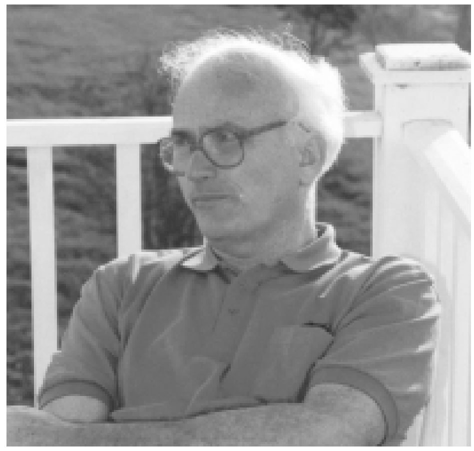
George Needler, the founding director of the WOCE International Planning Office, died on June 7, 2002 in his native Canada. His contribution to the initial development of WOCE was of enormous value.

George was born on 2 February 1935 in Summerside, Prince Edward Island into a family of marine biologists and fisheries scientists and was raised in the small Atlantic Canadian towns that were home to Fisheries Research Board Stations. He studied Mathematics and Physics at the University of British Columbia and his experiences working as a summer student assistant in the Pacific Naval Laboratory convinced him of the wisdom of pursuing a career in theoretical physics. After obtaining BSc and MSc degrees, he went to McGill from which he received his PhD in High Energy Field Theory in 1963.

While at McGill, he was recruited to join the Bedford Institute of Oceanography (BIO) that was just being established. After joining BIO in 1962, he was almost immediately sent to the UK National Institute of Oceanography Wormley, UK to learn the science of ocean circulation under Michael Longuet-Higgins, George Deacon, John Swallow and Jim Crease. Returning to Halifax, he led a small theoretical oceanography group and established a strong link to graduate student training by teaching a course in ocean dynamics at Dalhousie University.

As a young scientist entering the field of physical oceanography, he attacked the problem of establishing the large scale dynamical balances involved in the thermohaline circulation and made major contributions to the development of ocean 'thermocline' theory. His early interest in the use of tracers for determining ocean circulation led to his participation in the planning and review of the GEOSECS and TTO programmes of the 70s and early 80s.

George was especially gifted in bringing scientists together to contribute their knowledge and expertise to collaborative programmes and to issues important to society. From 1975-1985, he was heavily involved in the assessment of the risks associated with the dumping of low level radioactive wastes in the ocean and the burial of high level wastes in the seabed. He chaired both a GESAMP (Group of Experts on the Scientific Aspects of Marine Pollution) working group and an IAEA (International Atomic Energy Agency) committee that provided the scientific basis for these assessments and established dumping limits for low level radioactive waste in the ocean. In this task, he both maintained the integrity of the scientific assessment and developed a better understanding of the role of mixing and circulation in the ocean.



George at a WOCE Core Project 1 meeting at BIO in 1989. (Actually at Liz Tidmarsh's (Gross') house at Mahone Bay, NS. Canada)

It was his role in the development of ocean climate science that is of special relevance for WOCE. He was part of the SCOR working group that planned and co-ordinated the oceanographic components of the GARP Atlantic Tropical Experiment (GATE) in 1974 and was also part of the POLYMODE programme in the North Atlantic.

WOCE established its International Planning Office (IPO) at the UK Institute of Oceanographic Sciences in 1984 (where George worked in the early 1960s). The success of WOCE as a global oceanographic experiment to describe and better understand the oceans' general circulation as a key element of the earth's climate system is to a large extent due to the firm foundation set during early years with George's strong input. George had a remarkable skill in formulating a problem so that it was clear where solutions might be possible. He was also energetic in finding people, many at the beginning of their scientific careers, who would contribute to these solutions.

It is remarkable how the initial formulation of the goals of WOCE has stood the test of time.

With the IPO established in a leading research institute there was ample opportunity under George's directorship to challenge and argue the many questions that arose in the formulation of WOCE's Science and Implementation Plans. Ideas evolved from science to its implementation via a bottom-up approach involving many people. Many who made WOCE successful were spotted and involved by George his drive to get down to the important issues. In that sense the carefully argued science of WOCE was essential in bringing WOCE to its successful conclusion.

When the IPO changed from a Planning to a Project Office in 1989, George focused on further developing the scientific background as WOCE Chief Scientist. He returned to Canada in 1992 and later was very involved in the development of Ocean Observing Systems.

Those who worked in the IPO with George will have an image of him on the telephone with his feet on his desk and a much-chewed pen in his mouth. With this he made complex annotations to manuscripts in a script small enough to cause the IPO secretaries (first Sylvia Harvey and later Sheelagh Collyer) much difficulty. In his youth George had been a very good golfer and was happy to recount his exploits and achievements in tournaments throughout Canada.

It is indeed a tragedy that his life was cut short so that he will not be in San Antonio for the final celebration of the achievements of WOCE to which he contributed so much.

George is survived by his children Mary Kate, Kirstie, Ian, and Peter; first wife, Margaret and second wife Katherine.

How did WOCE turn out?

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Introduction

The World Ocean Circulation Experiment was by far the largest oceanographic programme ever carried out. Its ambitions combined a truly global reach with a wish to resolve many of the remaining problems concerning detailed physical processes in the ocean. I was asked to summarise how well the Experiment has met its goals. Answering such a question is extremely difficult: The concept of WOCE dates to the late 1970s; many hundreds of people were involved in formulating the goals, reducing them to practical terms, making budgets and negotiating collaborations, contributions, and getting the work done. Because it took a generation to go from conception to the present status (and many more results will be coming in for at least another decade) it is not really possible to separate WOCE from the evolution of the field as a whole. Presumably every individual who participated, whether their role was to serve for years on the various steering committees, or that of a watchstander at sea, or both, had some view of what WOCE was meant to do. Making no claim to speak for anyone but myself, I will try to give an overview of how I think we are coming out of it all. (This comment is a modified and extended version of a note that appeared in the US WOCE Annual Report for 2001).

To understand the rationale for WOCE and the elements of its formulation, a bit of context is necessary. By the late 1970s, the meteorological community had planned and carried out a large experiment (First GARP Global Experiment, FGGE) under the Global Atmospheric Research programme (GARP), specifically directed at improving weather forecasting. The oceanographic role was a marginal, supporting, one (cynics argued that oceanographers were permitted to participate only because the meteorologists needed the research vessels). The meteorological community then began turning toward the second GARP goal, which was directed at understanding climate change. This period was one in which a few farsighted individuals, but especially the late Roger Revelle, had begun calling attention to the ongoing 'great experiment' of increasing atmospheric CO_2, and suggesting that we badly needed to understand what the implications would be. (An example of the state of knowledge can be found in the so-called Charney Committee report (Ad Hoc Committee, 1979).) Unlike weather forecasting, it was difficult to argue that the oceans were not a central element in climate change.

The oceanographic community at this time was emerging with mastery of the technologies capable of understanding time variable oceanic motions on scales from internal waves to the mesoscale, including boundary currents and the like. A number of important experiments had taken place, labelled variously MODE, IWEX, ISOS, etc. exploiting the newly available current meters, floats, bottom pressure sensors, CTDs etc.. The science had clearly shifted away from the large-scale exploration mode of hydrographic sections obtained from ships as instanced by the 1957 International Geophysical Year, to the 'physics' of eddies, baroclinic instability, internal wave interactions and mixing, etc., that is, toward processes.

In the minds of some however, there was a strong suspicion that the era of large-scale exploration, far from having produced a definitive picture of the large-scale structure and circulation of the oceans adequate for understanding processes, had provided a gravely distorted, inadequate, view. The basis of this suspicion was the results from the very same process experiments such as the Mid-Ocean Dynamics Experiment (MODE), the International Southern Ocean Studies programme (ISOS), and others: The system appeared to be highly time-dependent, and as such could only have been grossly undersampled by traditional sampling methods (see Munk, 2002, for another discussion). It was clear that almost nothing was known about how the ocean might be changing on basin and larger scales. The CO_2 transient and other large-scale climate system changes, raised the spectre that the ocean was undergoing large-scale secular changes, perhaps everywhere, and that with the existing observational system ('system' is too grand a word, however), neither we nor any future generation would be in a position to say much of anything about what those changes were, how large, and where, much less why they were taking place. It appeared that global-scale observations spanning at least several years, would be required, observations adequate to both determine the major elements of the oceanic general circulation and its property fluxes, as well as the extent to which they could be inferred to be steady-in-time (or the opposite). Without such a capability, the oceanographic response to questions about how the system would respond to increasing CO_2 and related issues would have to be either pure fiction or pure silence.

Extended debates took place both in various national, and international settings concerning, (1) the importance of global-scale ocean observations - typically relative to the importance of the regional process studies which many thought were more urgent, and (2) the extent to which a global circulation experiment was even feasible. Some of this debate was quite fierce, and not everyone was pleased with the final programme plan, which laid a heavy (but not complete) emphasis on the global observations. (One prominent scientist argued that the existing hydrographic data base was "perfectly adequate." A major oceanographic laboratory director wrote to the Administrator of NASA saying that altimetry would never succeed.)

The issue of practicality was resolved by inferring that altimeter and wind-measuring satellites would work; by calculations that a coordinated ship-board hydrographic and chemical programme could be carried out over a period of 3 to 5 years if the burden were shared internationally; by the deployment of large-numbers of floats; and by the conclusion that atmospheric "reanalyses" would provide sufficiently accurate surface boundary conditions. The steering committees accepted the view that by the end of the programme or around the year 2000, ocean modelling would have advanced to the stage that all of these (and other) diverse observations could be combined into a consistent global view by combination of the data with models ("state estimation" or data assimilation). These latter elements were treated with benign neglect, because of arguments that they would be useless without the global observations, and that the modelling community was progressing sufficiently satisfactorily without the need to overlay a large international planning effort on top of it.

After much debate over several years, what emerged was the intention: (1) To provide a "snapshot" of the basic temperature and salinity structure of the oceans, both in watermass volume terms, and spatial structure as used in conventional geostrophic calculations. (2) To provide a picture of the variability that would extend to the globe the fragmentary regional description that had emerged from the field programmes of the 1970s and 1980s. (3) To deduce, as far as possible, the absolute (total) flow, over as short a time span as was practical. (4) To determine the regions of major air-sea transfer.

A fundamental underlying purpose of (1) was to provide a baseline of the oceanic thermodynamic state in the early 1990s, sufficient that future generations could use it to determine where, and by how much, the ocean heat and salt content was shifting with time. All of (1-3) were intended to make it possible to produce global tests of model basic states and variability. The 1988 WOCE Implementation Plan carries a full list of what was hoped for.

One must recall that WOCE did include a number of extremely important regional and process experiments, such as the Brazil Basin, Subduction and Purposeful Tracer Experiments. Furthermore, as had been anticipated, a number of regional experiments took place in parallel with WOCE, partly relying on WOCE for the larger-scales, and providing information of use to everyone. Where to draw the line between programmes is not very clear, and there seems to be no particular reason to do so. But in the interests of space, I focus here on the global observation element of WOCE.

The recent books edited by Siedler, Church and Gould (2001), and by Fu and Cazenave (2000) represent preliminary depictions of the WOCE results. Voluminous as these works are, much more is coming. It will take another 10-15 years before anything like an adequate rendering of the WOCE accounts will be possible.

A secondary goal (or hope) was that having established a global-scale system, post-WOCE, it would be sustained as needed. I will return to this issue at the end.

Major Elements

Thermodynamic and Chemical Description of the global ocean

The hydrographic programme, including chemical tracers, and a serious XBT supplement in the upper ocean, was the central element of the thermodynamic measurements. Between the time of the last, sporadic, international attempts to measure systematically the bulk hydrography of the oceans (IGY, the International Indian Ocean Expedition, and the Eltanin Surveys of the Southern Ocean) and the start of the WOCE field programme, it had become clear that the ocean contained a strong mesoscale eddy field. Given the sampling requirements dictated by the presence of eddies, it is not exaggerating to say that until WOCE, there had never been an adequate hydrographic sample of the ocean. (By "adequate," I mean that the long wavelengths in the temperature/salinity/density fields should have been measured without significant spatial aliasing.

Computations of the geostrophic flow require taking horizontal derivatives of these fields. Even where the large-scale properties appeared to have been delineated usefully, as in the IGY, the dynamically essential derivative fields were seriously corrupted.) The WOCE objective therefore was interpreted to require the acquisition of long-hydrographic lines with spacing adequate to sample the mesoscale, and to permit thermal wind calculations to be made with adequate accuracy (not clearly defined) on scales of the ocean basin. The nominal spacing of the stations was taken as 50km, which it was recognised is somewhat too large, but was a practical compromise. XBTs were used to refine the spacing in the upper ocean.

The final WOCE coverage has been displayed many times and is not repeated here. While differing in detail from early schematic coverage plots, it is qualitatively very similar to them. The main issue was that for budgetary reasons, it took 7 (rather than 5) years to finish the coverage. This "blurring" is a problem in attempts to do global calculations (one is forced to assume that the trans-oceanic property transport integrals are unchanging) an assumption that cannot be rigorously true. We await further attempts to better quantify the errors incurred. In addition, many analyses of the individual sections have begun to appear. No one has yet attempted a re-estimate of the global water masses, as last done apparently by Worthington (1981); presumably such a compilation will be forthcoming as part of the new climate reference state.

Variability

When WOCE began, we had the results of a few moorings scattered around the world (e.g., Schmitz, 1988) and a very small number of moored arrays (e.g., Fu et al., 1982). Entire ocean basins (e.g., South Pacific, Indian Ocean, Southern Ocean) were almost devoid of any direct measurements of variability. Apart from work with tide gauges in the tropical Pacific (e.g., Wyrtki, et al., 1988), almost nothing had been measured of variability on time scales exceeding a few months. Again, apart from the Pacific tide gauges, and some fragmentary results of the North Pacific XBT lines, there was almost no evidence at all for variability on space scales exceeding about 100km on any time scale. In other words, most of the frequency/wavenumber spectrum of oceanic variability had never been estimated - anywhere.

Today, largely as a result of the TOPEX/POSEIDON altimeter mission, there are global maps (e.g., Fig. 1 see page 16) of the total variability almost everywhere, of global average spectra, and too numerous to list, estimates of regional characteristics. WOCE did succeed in filling out the frequency/wavenumber space almost completely (down to spatial scales of about 20 km, and up to the size of the entire ocean, and ranging from about 20 days to the still-growing record length). All by itself, this is a considerable achievement. This variability is of course, that of the geostrophic surface flow; but along the way we learned a great deal about its vertical structure, extending to the seafloor. One particular discovery, worth singling out, was the clear demonstration (Stammer et al., 2000; Tierney et al., 2000) of the remarkable degree of barotropic variability present, especially in the high latitude oceans. This qualitative element of the circulation had been missed prior to WOCE - because it has almost no density field signature.

The WOCE designers had hoped that the altimetric missions would coincide with flight of a direct wind-measuring satellite. This hope was partially met, but the original high-accuracy mission (NSCAT) failed after nine months. Fortunately, the launch of a new one, after the inevitable delays, is providing the intended observation of simultaneous wind-forcing and ocean response, because the TOPEX/POSEIDON mission is still operating 10 years later (and now with a successor, Jason, as well.) WOCE thus will have eventually provided a much-improved understanding of the structure of the wind over the ocean, and of the oceanic response. Improvements in the wind field have many indirect consequences (e.g., tests of atmospheric models, and improved ability to compute air-sea fluxes of gases), but there is not space here to address these.

Western Boundary Currents

Determining the structure and transports of western boundary currents, particularly the deep ones, were a major goal. A number of arrays were deployed across many, but not all of such structures (see the Implementation Plan for positions). Whitworth et al. (1999) is a reasonably typical result. A qualitative conclusion is however, that even two years of record is too short to confidently claim determination of a stable, long-term, average flow. That we have not sustained these measurements indefinitely after WOCE can be considered a failure.

Tides and mixing

Ocean tides were never regarded as part of the WOCE description. But as a very important by-product, the altimeters have essentially solved the global tidal distribution problem (e.g., Shum et al., 1996), which is the largest contributor to sea level variability variance. Unexpectedly, these solutions dovetailed nicely with the now nearly overwhelming evidence (e.g., from the WOCE Brazil Basin Experiment; see Ledwell et al., 2000) that the ocean below about 1000m mixes primarily at its boundaries. A strong inference therefore, is that processes occurring at millimetre and centimetre spatial scales over minutes and hours, probably determine much of the ocean circulation on spatial scales of thousands of kilometres with time scales of years to millennia. This inference is a profoundly different descriptive statement than can be found in any existing oceanographic textbook.

Absolute Pressure Gradient at Depth

The deep float experiment was intended to provide an independent absolute pressure level for the large-scale general circulation by geostrophic inference from the large-scale float movement. Only regional estimates have so far appeared (Davis, 1998, Bower et al 2002), perhaps because many floats are still operating. Eventually, there should be a directly measured pressure surface to be compared with that emerging from the altimeter with data assimilation (see below).

Surface Velocity

A major new description from greatly improved surface drifters has emerged; see Lagerloef et al. (1999). The combination of the measurement of total velocity by *in situ* instruments and of the geostrophic component by altimetry is permitting direct separation of the ageostrophic component in the surface boundary layer.

Fluxes

Oceanic movement of heat (enthalpy), salt/freshwater, etc. are an important descriptive statement. Global scale estimates of the divergence of these fluxes are now mappable (e.g., Josey et al., 2001; Ganachaud 1999) and are quantitative. Note in particular, the realisation (primarily from model studies, e.g. Jayne and Marotzke, 2001) that the fluxes and flux divergences are extremely time variable.

Shortfalls

Any field programme has shortcomings. Inevitably, there are weaknesses in the data available as finally obtained for basic description. Among the most conspicuous are,

- North Atlantic hydrography: For non-scientific reasons, we failed to adequately sample the North Atlantic Ocean. The absence of a WOCE-standard hydrographic line at 36°N is a serious hindrance to completing global circulation estimates.
- Equatorial Region: Despite the presence of a few floats near the equator in the Atlantic, WOCE did not succeed in producing adequate measurements of the cross-equatorial flow fields and their variability anywhere. A major reason for this was the focus of the tropical experts on the ENSO problem, and on the ocean above a few hundred meters within a few degrees of latitude of the equator.
- The WOCE plan requested deployment of a series of deep-water moorings capable of determining the vertical structure of open ocean variability. Almost none of these moorings were actually deployed.
- Direct surface flux divergence estimates by bulk formulas were not made on a global scale. Although serious regional observations were made, e.g., as part of the WOCE Subduction Experiment, no global programme was put in place - on the advice of experts that too many technical problems remained to justify such an effort. (This decision appears to have been the proper one.)
- Few of the coast-to-coast sections were repeats of earlier measured sections, sparse as those were. (The 48°N section was a notable exception; see Koltermann, et al., 1999). Thus documentation of the decadal and sub-decadal thermodynamic variability as seen in the North Atlantic (e.g., Parilla et al., 1994; Joyce et al., 1999) remains elsewhere almost non-existent. More generally, the repeat hydrography component (that is, of sections measured several times within the WOCE period) was only carried out in sporadic form. There is a consequent gap in direct determination of hydrographic variability over months to years.
- Some of the hopes for a new generation of *in situ* observing tools (free-falling and self-propelled, easy-to-use profilers and water samplers); expendable current meter moorings, etc. were not realised in time for WOCE itself.

Now, and Forthcoming

Despite the lapses and the inevitable frustrations, it is important to recognise how much has been achieved. Because the results have been emerging piecemeal over the last 10 years, textbooks are beginning to reflect much of the new knowledge, and it becomes difficult to separate the WOCE results from more general oceanographic history.

For the first time in oceanography, we have succeeded in measuring the complete range of spatial scales making up the ocean circulation - 10,000km to about 20km, globally if irregularly distributed, with necessarily spatially sporadic measurements down to millimetre scales. The era in which some physical scales were completely unmeasured has finally ended.

We also have:

- A nearly complete survey of the temperature, salinity, nutrient, oxygen and carbon fields, coast-to-coast, top-to-bottom all completed within about 7 years. The interval is shorter than any plausible estimate of major change in the main thermocline and below; residual spatial aliasing appears tolerable.
- Complete global estimates of the variability, including not just the mesoscale, but all space/time scales from about 20-10,000 km, 20 days to 8+ years, as both global average and regional frequency/wavenumber spectra. (There is a loss of detail with increasing depth.)
- The distribution of the most important transient tracers (tritium/helium-3 and chlorofluorocarbons) in all oceans.

- A qualitative and quantitative shift to a picture of the ocean as dominated in most places by its temporal variability.
- Near complete determination of global ocean tides.
- A greatly improved bottom topography (Smith and Sandwell, 1997).
- An apparently firm commitment by governments to sustain the altimetric and wind-measuring satellites.
- The beginnings with Argo, and other programmes, of the ability to measure the *in situ* ocean without the sampling strait-jacket of purely shipborne observations.

Although not part of traditional descriptive physical oceanography, one should also compare the available general circulation model descriptions of 1979 with those available today, both on the basin and global scale. The testing of higher skill models requires a much better database than the testing of low skill models. We have come far in both pieces of the picture.

Combined with the 'description' now embodied in the much more realistic general circulation models, we are now able to produce three-dimensional time-evolving estimates of the oceanic general circulation everywhere with considerable skill (Stammer et al., 2002; see Fig. 2). To a considerable degree, the wager that modelling, computers, and analysis techniques would be adequate by about the year 2000 for global scale state estimates has paid off. (We could have been further along than we are; but this is always going to be true.)

One hope of some of the organisers was that the physical oceanographic community would gradually re-orient itself more towards viewing the ocean as a global phenomenon. This re-orientation has been very slow to happen - few oceanographers take the world ocean as their domain of expertise. Several reasons for this lag are obvious: the world ocean is a very complicated place, with major regional variations in dynamics and kinematics. Grasping it all is very difficult. The temporal changes on large scales in the hydrographic fields, while real, appear dominated by time scales much too long for ordinary grant funding cycles (or promotion and tenure timescales). Observing the global ocean requires using spacecraft, or working with large-scale collaborative structures like Argo.

Like WOCE itself, coalition science is not so easy, and the rewards often lie far in the future. A challenge to oceanographers and climate scientists working in the post-WOCE period is to find a way to maintain, upgrade, and then sustain the global aspects which WOCE dealt with momentarily.

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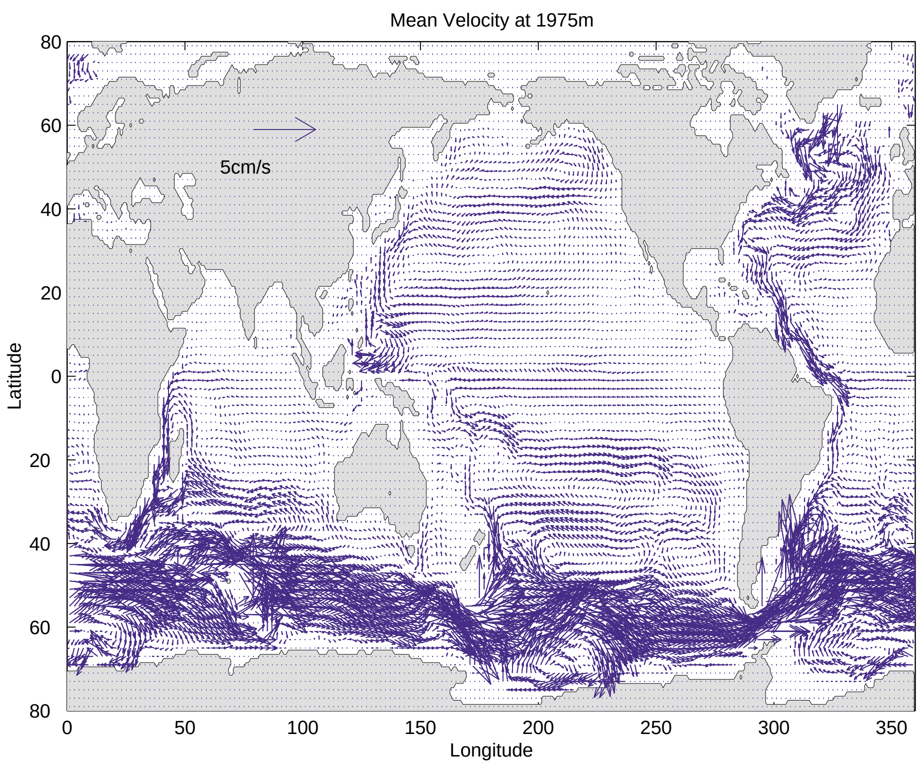

Figure 2. Mean flow from 1992-1997 at 1975m from the combination of a large fraction of the overall WOCE data set and a general circulation model (Stammer et al., 2002). Such syntheses are now available day-by-day for the global ocean, and will be one of the major WOCE products as they become more complete and skillful.

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WOCE AND BEYOND - THE FINAL CONFERENCE

(See Programme on page 30)

The week of November 18-22 will see members of the WOCE community and many people from other global ocean and climate programmes congregate in San Antonio, Texas, for the final WOCE Conference. This meeting, in the Henry B. Gonzalez Conference Center next to the world-famous Riverwalk, promises to be an exciting conclusion to the WOCE era, and provides a great opportunity for the WOCE community to assess what has been achieved and to discuss what the future holds for ocean and climate research.

The organising committee has recruited a host of stimulating speakers to sum up what has been learnt during WOCE (see the Conference website at http://www.WOCE2002.tamu.edu). There will also be ample space for people to display posters of their own exciting results. Apart from the scientific results, there will be displays devoted to the WOCE atlases and WOCE data, and all registered attendees will receive a set of DVDs containing the multiple data sets obtained during the programme, including satellite altimetry and wind data. The data management gurus also will be on hand to demonstrate how to gain maximum advantage from the DVDs.

Over 130 posters have already been submitted, but we can certainly accommodate many more. To this end, the closing date for poster submission has been extended to 30 September, and there is no limit on how many posters an individual may submit. For those not submitting a poster, registration via the web is available until 8 November, 2002.

November is a great time of year to visit the Texas Hill Country, so come to San Antonio and join your colleagues in celebrating more than a decade of WOCE research.

For further details please contact the International WOCE Office (woceipo@soc.soton.ac.uk)

Has WOCE helped deliver ocean models suitable for predicting climate change?

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1. Introduction

In this article we discuss from a modelling perspective the first goal of WOCE, which is 'to develop ocean models suitable for predicting climate change and to collect the data necessary to test them'. [See Wunsch article on page 4]

At the start of WOCE in the mid-1980s, climate modelling was in its infancy. Very few centres had the resources to attempt global ocean or climate simulations, and those that did were severely limited by the computing power available at the time. However, as the founders of WOCE correctly foresaw, the WOCE period saw a huge increase in the computer power available and in the sophistication of the models used. This has led to developments in the realism of models, largely in the form of better resolution (see Section 2) and more sophisticated representation of the physics of the ocean (Section 3). Section 4 discusses the ways in which the WOCE observations have impacted on the development of models, and Section 5 presents a brief summary and look to the future. We can only give a very brief overview here. The reader who is interested in following up in more detail is referred to the reviews by Griffies et al. 2000, Böning and Semtner 2001 and Wood and Bryan 2001.

2. Resolution

During most of the WOCE period global ocean modelling was carried out by two broadly defined groups:

- 'Climate modellers', typically working in climate research institutions, who focused on the ocean's role in the coupled climate system, and who required model runs of 100-1000 years in order to assess long term climate variability and change
- 'Ocean modellers', typically working in oceanographic institutions and universities, who focused on achieving the best possible model of the present day ocean circulation, requiring model runs of only a few decades, and who could therefore exploit much higher model resolution

In the last few years this distinction (and the 'division' between the two communities) has become less marked, as increased computer power and better models have made coupled models a valuable tool to a wider range of researchers, and climate modellers have understood the importance of modelling and understanding the variability of climate over the recent instrumental period. Nonetheless, the distinction between the above 'prognostic' and 'diagnostic' uses of models is important, as the prognostic mode will always place the strongest demands on computer time for a given model resolution.

The most obvious way in which modellers have exploited increasing computer power is by increasing the resolution of their models. The pioneering coupled climate model experiments at the NOAA Geophysical Fluid Dynamics Laboratory (e.g. Bryan et al 1988) used a horizontal resolution of around 4˚, clearly insufficient to resolve boundary currents and mesoscale processes. Such models typically produced a rather sluggish ocean circulation with an over-diffuse main thermocline and insufficient poleward heat transport, leading to significant errors in the sea surface temperature fields. Common practice during the 1990s was to apply non-physical surface 'flux adjustments' to these models in order to achieve a present day model climate that was reasonably close to reality (Sausen et al 1988).

More recent coupled models have used ocean resolutions of 1-2˚, and this, combined with improved sub-grid scale parameterisations (see Section 3) has resulted in models that can produce a reasonable simulation of large-scale ocean heat transports. This appears to be a key factor in allowing more recent models to be run without the need for flux adjustments (see IPCC 2001, chapters 7 and 8).

In parallel with these developments, ocean-only models have moved from idealised basin-scale models with resolutions of up to 1/3º in the 1980s (e.g. Semtner and Mintz 1977, Cox 1985) to global, 'eddy-resolving' models with resolutions of order 1/10˚ which are being developed today (see, e.g. Böning and Semtner 2001). Very few coupled climate integrations have been attempted to date with ocean resolutions less than 1˚(e.g. Washington et al. 2000); the finest ocean resolution used in a century-timescale coupled model integration is 1/3˚ (M.J. Roberts, per. com.). Such integrations represent a major computational task on today's supercomputers, yet they can still only be described as 'eddy-permitting' i.e. the models produce mesoscale variability, but the Rossby radius is not fully resolved and the eddy energy is typically too low.

Recent developments in supercomputing such as the Japanese Earth Simulator computer (http://www.es.jamstec.go.jp/esc/) mean that extended eddy-resolving climate integrations will probably soon be possible, building on the valuable experience of such resolution gained during WOCE. Issues of storage and analysis of the model output, rather than computational speed, may become the limiting factor in determining what can be achieved, if technology in these areas cannot keep pace with the advances in data processing speed.

The question 'what ocean model resolution is required to make climate predictions?' is still very much an open one. Advances in sub-grid parameterisations (Section 3) have led to great improvements in the basic climate simulations achievable at relatively coarse resolution. Ultimately, predictions made using such models will have to be tested against higher resolution models in which parameterised processes are explicitly resolved (e.g. Roberts and Marshall 2000, Gent et al 2002).

3. Model formulation and physics

The WOCE period has seen advances in both the sophistication and the diversity of ocean models. Models with different types of vertical coordinate (potential density, terrain following and hybrids) have matured alongside the previously ubiquitous geopotential/depth (z) coordinate. Each model/coordinate type is motivated by a different aspect of the physics of the ocean and we have developed an understanding of the properties of each type of model (e.g. Willebrand et al. 2002).

The importance of flows through narrow sills (e.g. the Denmark Strait) for the large-scale circulation has been demonstrated (e.g. Roberts and Wood 1997). Models which use a z-coordinate (still the majority) have difficulty in representing the down slope progression of such overflow water without excessive mixing, but recent developments in bottom boundary layer modelling (Beckmann and Döscher, 1997; Killworth and Edwards, 1999) promise an improvement in this area (Dengg et al. 1999). The down slope flows are handled more naturally in an isopycnic coordinate framework. However, the physics that determines the strength of the sill overflow is still not fully understood, and ultimately high resolution in the sill regions may be the only option.

Important improvements have been made in the way sub-grid scale mixing is parameterised in ocean models. The first step towards this was taken by Redi (1982) and Cox (1987), who devised a scheme to mix tracers along isopycnal surfaces rather than level (z) surfaces. Gent and McWilliams (1990) developed this further to produce a scheme that allowed potential energy to be extracted adiabatically from the large-scale density gradient, mimicking the effect of (unresolved) baroclinic instability. As a result of these developments, and improved numerical methods due to Griffies et al. 1998, modern ocean models with a resolution coarser than their Rossby radii are able to dissipate the inevitable enstrophy (the variance of the vorticity) cascade to the grid scale without introducing spurious diapycnal mixing. Removing this spurious mixing has played an important part in correcting the previous inability of ocean climate models to produce realistic vertical thermohaline structures and heat transports (Böning et al. 1995, Jia 2000, 2002, IPCC 2001, see figure).

The scales of processes believed to be responsible for diapycnal mixing are such that these processes are unlikely to be resolved in models in the near future. During WOCE, new parameterisations of surface boundary layer mixing have been developed (e.g. Blanke and Delecluse 1993, Large et al. 1994), although there is no consensus as to the optimal method. Beneath the surface boundary layer, observational understanding obtained during WOCE has emphasised the strong horizontal inhomogeneity of diapycnal mixing (e.g. Polzin et al. 1997), but only very few numerical experiments have been made as yet to explore the importance of this inhomogeneity for the large scale circulation (Hasumi and Suginohara 1999). Development of parameterisations in this area is still limited by lack of observations, despite the great progress made during WOCE.

Sea ice is a vital component of the climate system. Although ice-covered regions were largely outside the domain of the

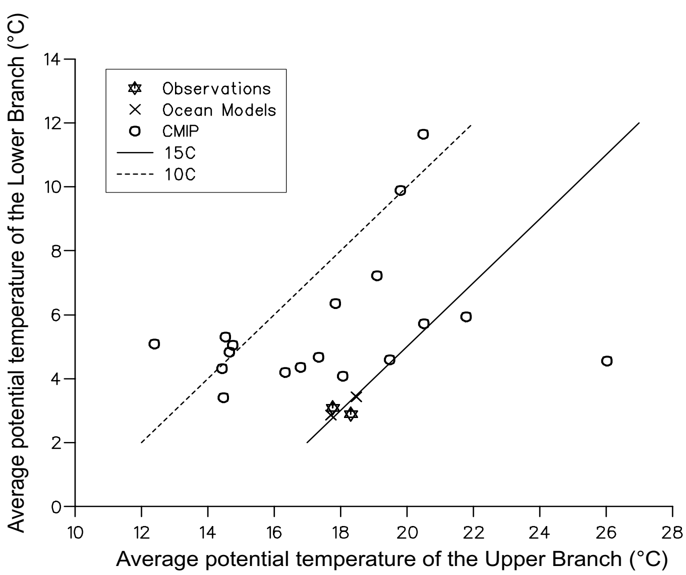

Figure caption:

Volume-weighted average potential temperatures of the upper (northward-flowing) and lower (southward-flowing) branches of the North Atlantic overturning circulation near 25ºN, in a number of coupled climate model runs submitted to the Coupled Model Intercomparison Project (CMIP). For a given rate of overturning, the northward heat transport is proportional to the temperature difference between the two branches. The solid line represents a temperature difference Tupper -Tlower = 15ºC, while the dashed line represents Tupper -Tlower = 10ºC. Two observational estimates are shown. Note that in most of the models the lower branch is too warm and Tupper -Tlower is less than the observed value of 15ºC. Two ocean-only runs are also shown (crosses). These were initialised from observations and have only been integrated for a few decades; hence they remain close to the observed values. Coupled models that maintain a temperature difference close to the observed values generally produce realistic heat transports and can be run without flux adjustments (see IPCC 2001, Table 8.2). [From Jia 2002].

WOCE observations, sea ice modelling has developed considerably during the WOCE period, and climate models are now beginning to employ more sophisticated representations of both the thermodynamics (Ebert and Curry 1993, Fichefet and Maqueda 1997, Bitz and Lipscomb 1999) and dynamics (Hibler 1979, Hunke and Dukowicz 1997).

4. Observationally-based tests of models

Did we need WOCE to tell us what was wrong with our ocean models? At the start of WOCE, probably not – the poor thermohaline structure and heat transports which were a common feature of most ocean climate models at that time were clear from what we knew about the ocean pre-WOCE, although their importance was not fully realised. The model developments described above have led us now to models that can maintain broadly realistic heat transports over multi-century model runs.

With an improved ability to simulate large-scale heat transports, modellers are beginning to give attention to the fresh water budget. There have been relatively few studies on this topic to date, partly because of the large observational uncertainties (Wijffels 2001) and the difficulty of analysing it meaningfully in an ocean-only context (since the salinity in uncoupled ocean models is generally forced by the discrepancy between observed and model surface values, the fresh water cycle in such models exists only because the models have inaccurate surface salinities). But it is becoming clear that the fresh water budget plays an important role in many aspects of variability on decadal and longer timescales, and some understanding of the water budgets in coupled models is beginning to emerge (e.g. Doney et al. 1998, Pardaens et al. 2002).

The global circulation schemes provided by the inversions of WOCE and pre-WOCE observations (MacDonald and Wunsch 1996, Ganachaud and Wunsch 2000) will perhaps provide the next target for models. However, as in all comparisons with observations, it is important to know and understand the limitations and uncertainties of the observational estimates. This should also warn us not to focus on the large-scale picture to the exclusion of local 'details'. Detailed regional analyses, such as have been performed for many regions during the AIMS phase of WOCE, improve understanding of the large scale picture, and can hold the clue to the causes of particular model errors. It can be enlightening to repeat such circulation inversions using global model output (e.g. Wilkin et al. 1995, Banks 2000).

It is in the above area that the most fruitful interaction between the models and observations should be possible, and yet has proved frustratingly difficult to achieve. Simply using a particular observation to show where a model is 'right' or 'wrong' is ultimately a sterile activity. Observations are based in the real world, but are beset by sampling limitations, and often the quantity of real interest (e.g. heat transport) can only be inferred by processing observations of some other quantity through some kind of filter (a model, even if it only resides in the mind of the individual scientist). Conversely models are not the real world, but they do provide a perfectly sampled and physically consistent set of data, and hence can act as an interpolator to aid interpretation of sparse datasets. To make best use of models to aid interpretation of observations, and observations to understand and improve models, is a challenging task, which we are still learning how to do. For example, the large transient tracer dataset collected during WOCE contains a wealth of information about the ocean circulation, but the theoretical and modelling ideas required to interpret the tracer data are still being developed (e.g. England & Maier-Reimer 2001, Meredith et al. 2001, Haine and Hall 2002, Wunsch 2002).

Direct assimilation of data into numerical models is a method that in principle can provide an optimal, dynamically consistent interpolation of sparse observations. Such assimilation is now used routinely to generate near-real time ocean analyses and to initialise seasonal forecasts. However, assimilation of data in order to understand the long-term mean flow, rather than daily-seasonal variability, is a more challenging task, since long-term model drifts will inevitably be reflected in the final solution (the drifts can be subtracted out for seasonal forecasting purposes). Nonetheless, valuable progress is being made in this area (e.g. Talley et al. 2001), and as computer power and models improve, this approach promises new insights.

To have confidence in the ability of models to predict future climates, it is not sufficient simply to show that the models can reproduce the present climate state. Ability to reproduce known climate change or variability from the past, given appropriate forcing, is important in order to show that the models are not simply being 'tuned' to produce a particular climate state. During the WOCE period, it has been shown that a number of climate models can reproduce many features of the history of surface air temperature over the past 150 years, given appropriate historical changes in natural (e.g. solar radiation, volcanic aerosol) and anthropogenic (e.g. greenhouse gas, industrial aerosol) forcing (IPCC 2001, chapters 8 and 12). More recently, climate models have been shown to reproduce some aspects of changes in ocean heat content over the past 50 years, as estimated from observations (Levitus et al. 2001, Barnett et al. 2001). More local changes in water mass properties have also been studied, and tentative attribution of the causes of the observed changes has been made (e.g. Banks et al. 2000, Rintoul and England 2002), but interpretation is restricted by the general sparseness (especially in time) of the historical data; this is another area where, to get the most out of the limited observations available, a strong and open interaction between modellers and observationalists should bear fruit in future.

5. Summary and forward look

During the course of WOCE, improvements in resolution and physical/numerical formulation have led to modern ocean models that are able to make a reasonable job of simulating the large-scale heat budget. This appears to have been important in the decreasing requirement for 'flux adjustments' in climate models. The fresh water budget is less well constrained by observations, and its long adjustment timescale makes it harder to develop models that simulate it well. Given its importance in decadal to centennial climate variability, further progress in this area is called for.

There has been no convergence yet on a single 'best' form of ocean model for climate studies, nor are there any clear answers yet to the question of what must be resolved and what can be parameterised. Even if it turns out that the current model resolution is adequate for climate prediction, higher resolution runs will be required in the short term to demonstrate this.

We are still learning how to make best use of data and models together, but there have been encouraging examples of what can be achieved. To get the most out of the WOCE dataset will require oceanographers with a good understanding of both the models and the observations.

Looking to the future, we believe that the following are likely to be important areas in ocean climate modelling over the next few years: More integrated exploitation of models and observations (including the use of models to help design observational campaigns), improved parameterisation of mixing processes (a need that has become clearer thanks to WOCE observational work), understanding the importance of mesoscale processes in climate through high resolution models, more flexible coordinate systems (e.g. adaptive meshes), inclusion of biogeochemical processes, and use of model hierarchies and ensembles to understand uncertainty in climate predictions.

Finally, we should attempt to answer the question of our title! The answer is yes, although we have by no means finished the process. During WOCE our models and our observational knowledge of the ocean have matured to a stage where the models and observations are starting to be able to interact, with each shedding light on the other. We are still learning how to do this, but the process is leading to improved understanding of the ocean's role in climate and hence over the long term improvements in our ability to predict climate.

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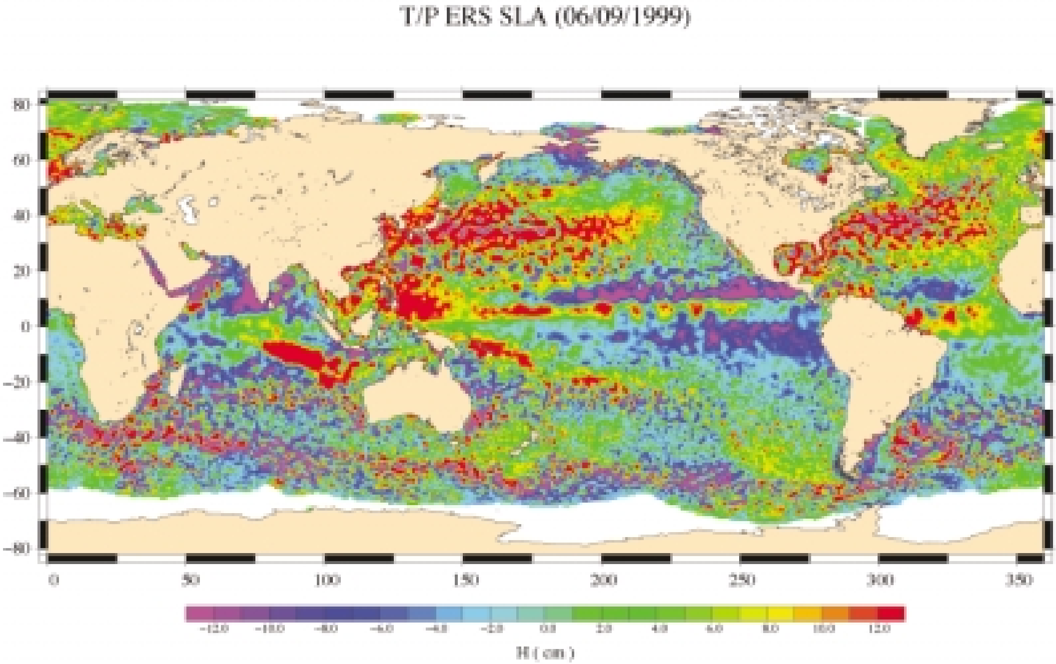
Contact: Mike Sparrow (mdsp@soc.soton.ac.uk)

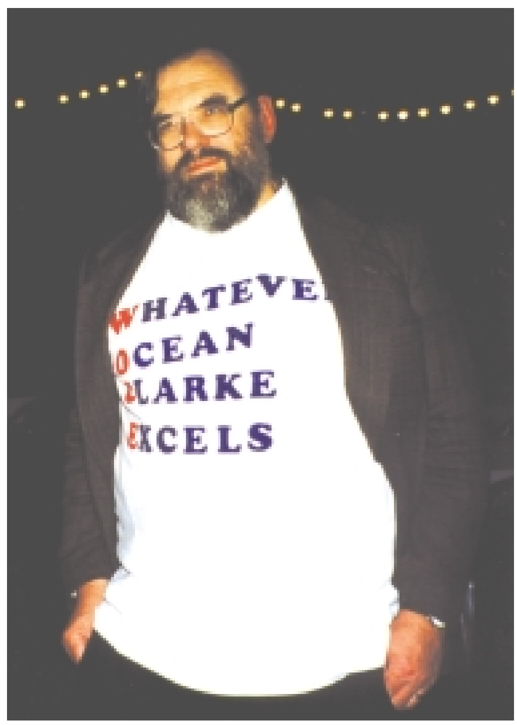
John Woods & Peter Killworth at the WOCE Conference, Halifax, NS 1998.

Roberta Boscolo & Penny Holliday enjoying the WOCE Conference dinner. Halifax, NS 1998



Wunsch, *Figure 1. Altimetric estimate from the combined TOPEX/-POSEIDON and ERS-1 satellites during one 10-day period in 1999 relative to a three-year average (in centimeters). The "pointillist" effect arises from the presence of the mesoscale eddy field and is superimposed upon larger scale background features. The ability to continuously produce charts such as this one is one of the notable WOCE achievements. (From CLS Space Oceanography Division.)*

Just married, former WOCE Newsletter editor, Roberta Boscolo and Dr Emilio Marañon in Venice, Italy, 7 September 2002



*Allyn Clarke, WOCE Conference, Halifax, NS, 1998 wearing his presentation shirt **W**hatever **O**cean **C**larke **E**xcels.*

WOCE Data Products Committee. DPC-9 IFREMER Brest Feb. 1996, This meeting was remarkable for the tremendous gale that uprooted trees and smashed windows.

WOCE SSG-11 IOS, Wormley, UK 1984. Carl Wunsch, (L).Francis Bretherton (head in hands), and Jim Crease. (R)

WOCE SSG-28 La Jolla Nov. 2001

(Above) John Church, (SSG Co-chair) Roberta Boscolo and John Gould, SSG-24, September 1997 in Boulder, CO. enjoying being tourists.

Some delegates swearing allegiance to the Halifax town cryer at the WOCE Conference in 1998.

Meeting at Chilton UK in Jan 1981 to decide on combination of satellite missions that would be needed to complement in situ measurements. Attendees included Pierre Morel, Michel Lefebvre, Carl Wunsch, Francis Bretherton, John Woods and Stan Wilson.

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* * COMING SOON * *

WOCE Observations 1990-1998
A Summary of the WOCE Global Data Resource

Are you looking for a convenient hand-held summary of WOCE observations?
Do you want to know quickly whether data exist in your region of interest?
Are you interested in when and where data were collected during WOCE?
If the answer is yes, then this document will be invaluable to you!

The data resource summary will guide you through the extensive WOCE field programme. It will serve as a quick-reference guide and companion to the WOCE Global Data being issued on DVDs and online later this year.

The document will be published in January 2003 to mark the end of WOCE. Electronic and hardcopy versions will be available.

WOCE International Conference, Paris 1988, George Needler and Bert Thompson both stalwarts of the WOCE IPO.

Terry Joyce, Woods Hole, Peter Koltermann, WOCE IPO and Gunnar Kullenberg, IOC at the WOCE International Conference, Paris, 1988

May 1982 Joint JSC/CCCO meeting, Tokyo, on large scale oceanographic experiments in WCRP. Francis Bretherton (L), joint SSG Co-chair and Pierre Morel (R), Director WCRP.

The WOCE IPO through the years

W. John Gould, Director, WOCE IPO, SOC, Southampton, UK. john.gould@soc.soton.ac.uk
Peter Koltermann, BSH, Hamburg, Germany. klaus-peter.koltermann@bsh.de

In August 1983 the first meeting of the WOCE SSG "welcomed the offer of J.Crease to establish a Science Planning Office at the Institute of Oceanographic Sciences, Wormley".

In January of the following year the SSG agreed that the office would

- "Provide support of the scientific planning of WOCE as it develops within the Scientific Steering Group and its associated groups to achieve WOCE goals.
- Provide facilities for visiting scientists to work with WOCE
- Take part in and develop data management plans as they are needed, arrange for the archival, inventorying, and availability of data to do WOCE.
- Inform oceanographic colleagues of progress of, and encourage participation in WOCE"

This was hardly elegant prose but it set the scene for almost two decades of support for WOCE. In the mid-80s, when the WOCE office was established, the concept of such an office was rather innovative. Everything had to be started from scratch. The office had to find people who knew answers to key WOCE research questions, and these answers had to be communicated quickly, whilst the progress of the project had to be documented.

By late 1985 George Needler was in place as IPO Director and Sylvia Harvey was the secretary to the Office.

George was joined by Peter Koltermann**,** seconded from Germany in 1988 (until 1991). In 1988 Bert Thompson started a series of extended visits (lasting until 1992) to the IPO. He became almost a member of the family of the landlord of the Kings Arms in Godalming where he stayed.

Word processors, let alone PCs, were relatively new and certainly not very powerful. At this time the precursors of email and internet were around but they worked differently from what we are familiar with today. So, Omnet helped communications within WOCE and helped IPO staff to stay in touch with the office when they were away. The generosity of IOS in covering the telephone bills was a tremendous asset. Pressing issues could be discussed and sometimes resolved within a day – but not always.

Essentially the WOCE Science and Implementation Plans were written on Omnet: Sections of text were edited and exchanged, regardless of time zones and finally ended up in a draft that was presented to the working groups.

E-mail was not available everywhere. In 1989, before the dissolution of the Soviet Union, WOCE arranged to have a modem-linked email box in Moscow. What a difference from sending telexes and having to transcribe them.

In October1985 the first Newsletter was published, starting a series that this issue will bring to a close. All are available on the WOCE web site.

As the start of implementation approached, the office became busier. Bruce Taft joined in 1989 (until 1991). His cigar smoke pervaded the IPO offices (yet another reminder of how the world has changed during WOCE!) All offices are smoke free zones now). As observations started to be made, data issues came to the fore and Penny Holliday joined the IPO in 1990 to concentrate on this aspect.

Sheelagh Collyer joined Sylvia as a temporary assistant in 1988 and eventually took over as WOCE secretary when Sylvia retired. For many years Sheelagh was the IPO's interface with the outside world and its corporate memory as staff arrived and left. That memory is now with Jean Haynes.

Throughout the life of the IPO, the challenges were not just scientific -creative improvisation was required to steer the office through the uncertainties of funding and at a practical level to provide travel funding and air tickets to people in far away places. It worked, with the help of many friendly people, and mostly with a touch of dare-devil determination by the staff.

George become WOCE Chief Scientist in 1989 when the office changed from a planning to a project office and Peter Koltermann assumed the Directorship (until 1991), followed by Nick Fofonoff (1991-1993) and John Gould (1993-2002). New support staff were seconded by Germany - Ilse Hamann (1992-4) and Andrea Frische(1994-1997). Andrea did a great deal of the planning for the 1998 WOCE Conference. Andrea was succeeded by Roberta Boscolo whose Italian flair for design was seen in the Newsletter layout, in WOCE posters and in the quality of the images in the WOCE book. Peter Saunders started working at the IPO in 1994, generously funded by the USA.

And so here we are at the present day - John Gould, Peter Saunders, Penny Holliday, Jean Haynes, Katherine Bouton working on the DVDs, and Mike Sparrow on the Atlas production, bringing WOCE and its IPO to a tidy end.

The IPO has been a great learning place, embedded in a research institute of which it became an integral part. The IPO survived and was revitalised by the move from Wormley to Southampton and by its co-habitation, from 1998 onwards, with the CLIVAR office.

We have produced many documents and meeting reports. Few make for gripping reading but they do document how we managed the programme and reached the decisions made at various turning points. Not all of our writing was "internal" to the programme. All of us scientists have had to become better at "selling" our science to governments and to the general public, and many "popular" articles have described WOCE. But, has WOCE yet gained the visibility outside the science community that it really deserves? We think not yet.

It is a source of great sadness to all of us that George will not be there in San Antonio to see the end of the enterprise that he started.

Finally we must thank the countries that over the years have supported the WOCE IPO, UK, USA, Japan, France, Germany, Canada, Australia, Argentina and of course, the WCRP.

The role of technology developments in WOCE

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John Gould, WOCE IPO, SOC, Southampton, UK wjg@soc.soton.ac.uk

Hindsight is a wonderful thing, but sometimes we fail to remember what we were doing just a few short years ago. It is undoubtedly true that since WOCE was conceived (in the early 1980s) our ability to observe the global ocean has been revolutionised. Indeed one might argue that it was the prospect of such a revolution that provided the motivation for doing WOCE.

Our new observational capability depends on technology developments during the WOCE era. For example, WOCE has benefited greatly from the quantum leap in navigational accuracy since the early 1980s when the only truly global, high accuracy navigational system was that provided by the transit satellite system. Fixes were intermittent (often separated by several hours) and were accurate to a few hundred metres at best. By the early 1990s GPS (albeit degraded by Selective Availability for civilian users) was available for a few hours per day and, when available, gave continuous fixes to an accuracy of order 30m. And now GPS navigation is available continuously to a few meters accuracy. For most applications navigation is no longer a problem.

Observations in WOCE have an underlying three-pronged structure – satellite remote sensing – *in situ* velocity fields and *in situ* scalar fields.

The earliest satellite remote sensed data over the oceans was of Sea Surface Temperature (SST). We have had numerous SST products from a range of sensors, each with a different spatial resolution and accuracy. Each product has its own special value, but now integrated global SST fields are becoming available constructed from both remotely-sensed and *in situ* data.

Satellite altimetry was pioneered by the 100-day mission of SEASAT in 1978 and then afterwards by GEOSAT. These missions demonstrated that satellite altimetry would be a useful tool for ocean circulation research. Finally during WOCE we achieved and surpassed the few cm precision predicted for the ERS satellites and then for Topex-Poseidon. We can look at seasonal and interannual variability in all weathers and the outstanding success of these satellite missions has resulted in continued funding for altimetry via the 2001 JASON-1 satellite, and for the 2002 GRACE gravity mission that will provide us with absolute velocity fields. Satellite altimetry is now an integral part of our armoury, and it is now almost unthinkable to write papers on basin and global-scale phenomena without reference to such data.

The ERS satellites, and subsequent missions such as QUIKSCAT, carried microwave scatterometers and since 1991 we have relied on such sensors to provide global wind fields. Present capabilities are within 1 m/s and 20° in direction of ground-based measurements. The advent of these satellite-based sensors, as well as the need for improved model formulations for air-sea fluxes, required improved ground-truth data. WOCE carried out considerable testing and deployment of suites of meteorological sensors on ships and buoys. The improvement in the estimated fluxes has been dramatic – errors in heat flux measurements have reduced from about 70-80 W/m^2 in the mid 1980s to about 10 W/m2 now (Weller, 1996). These improved figures meet the requirements for future long-term climate studies, but as yet only a small number of research vessels and other sites are equipped with the necessary instrumentation.

As one might expect from a project directed at the role of ocean circulation in climate, WOCE has contributed to major improvements in the direct measurement of ocean velocity fields. The first improvement was to surface velocity measurements which resulted from radical redesign of surface drifters. Work early in WOCE and in TOGA produced drifters with significantly-reduced vulnerability to wind and wave biases and a design that was much more robust, surviving about three times longer than its predecessors (Niiler et al., 1995). The new design was also cheaper. The instruments not only provided information on velocity within the surface layer and sea surface temperature, but many were equipped with salinity sensors. Perhaps the greatest innovation was the addition of pressure sensors capable of being submerged and yet retaining their calibration (the surface element of the new drifters was very small and hence often submerged to several metres). The pressure drifters played a vital role in helping define atmospheric fields in the Southern Ocean. At present, a global 'fleet' of about 600 such drifters is delivering data directly to researchers.

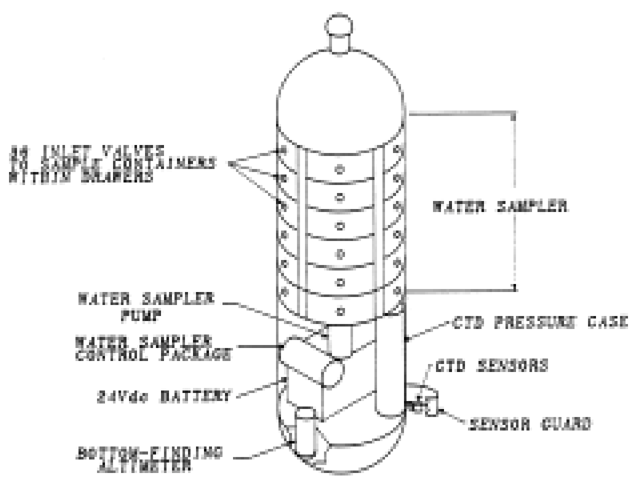


Figure 1 - The WOCE Hydrographic Sampler

In the late 1980s acoustic Doppler current profilers (ADCPs) were starting to be installed on the hulls of research ships and could provide shear profiles over the upper 2-500m of the water column. A major limitation in determining absolute velocities was due to uncertainties in ships' position and heading. The advances in GPS availability and accuracy and the ability to use GPS to define ships' heading to an accuracy of 0.1° (rather than the 2°) typical of a gyro-compass made these measurements of much greater value. (Firing, 1998). With this improvement in positional accuracy came the ability to use the ADCP in lowered mode (on a CTD/multisampler package) to obtain profiles throughout the water column. This led directly to the discovery of a new current, the Agulhas Undercurrent (Beal and Bryden, 1997).

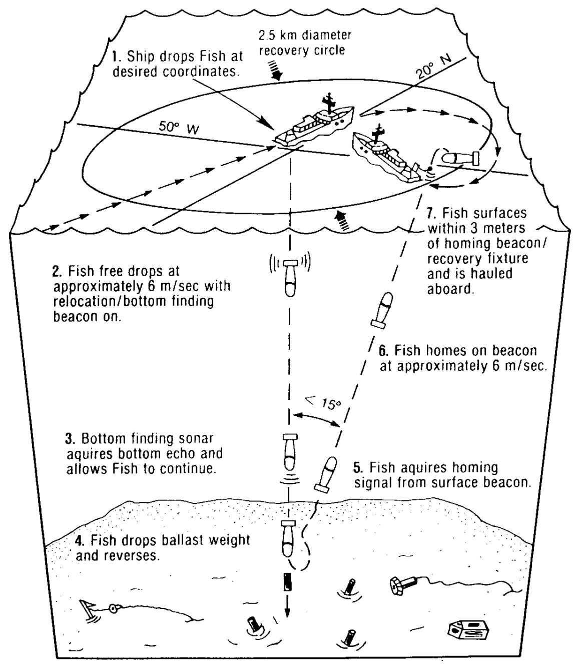
The formulation of the WOCE programme set an immediate technology challenge – to establish a means by which the global subsurface velocity field could be measured directly. Neutrally buoyant floats had that capability but in the pre-WOCE era these were tracked acoustically, thus limiting their deployment to the basin scale. The solution came from the development of the Autonomous Lagrangian Explorer (ALACE; Davis et al., 1992). These floats descend to depth, drift for typically 10-14 days, then change their buoyancy to rise to the surface where their positions are fixed by satellite. They then descend and repeat the cycle. The ascent phase was later used on profiling (P-ALACE) floats, through the addition of CTD sensors, to record the temperature and salinity structure of the water column and to return the data via satellite. Accuracies better than 0.01°C and 0.01 for salinity are attainable (Argo Science Team, 1998).

Around 1000 floats of various types (some acoustically tracked) were deployed during WOCE and these enabled subsurface flow fields to be objectively mapped on basin-wide scales. (Davis, 1998, Bower et al 2002). Floats similar to PALACE floats now form the basis of the global Argo array, a central element of the Global Ocean Observing System (GOOS). Argo already has 500 floats and by 2005 there will be 3000 units delivering 100,000 T/S profiles per annum to 2000m depth from all areas of the ice-free deep ocean at a cost of order $100 per profile. Argo undoubtedly owes its existence to WOCE developments.

For the third element WOCE depended heavily on a comprehensive, global high accuracy hydrographic programme that included the measurement of a suite of chemical tracers. It was carried out in partnership with the IGBP's Joint Global Ocean Flux Study (JGOFS). This, the WOCE Hydrographic Programme (WHP), required and stimulated technological developments. Ships were refitted to carry the large scientific parties needed and to extend their endurance from typically 30 to 45 days. Additionally, high-resolution repeat temperature data were obtained through the development of automatic XBT launchers for ships of opportunity such as those making up the Volunteer Observing Ship fleet.

Tracer measurements improved considerably during WOCE. Prior to the programme the measurement of Carbon-14 (McNichol et al., 1994) required about 250 litres of water per sample. A new technology, based on accelerator mass spectrometry at a facility at Woods Hole, MA, offered the same accuracy and precision but

Figure 2 - The "Fast Fish"



required only about 20 ml of sample! Carbon-14 measurements were then able to be made at approximately 60-mile separation along most of the WHP lines and have provided a second (the first made in the 1970s GEOSECS programme) snapshot of the oceanic bomb radiocarbon transient. Changes to sampling and analysis techniques have similarly improved the collection of CFC and He/Tr data, while deliberate experiments with SF_6 have led to new insights into mixing processes within the deep ocean (Ledwell et al., 1993; Polzin et al, 1997).

For WOCE to meet its goals, data collection and analysis is not enough. Data sets must be archived for use by future generations of oceanographers and assimilated into models. WOCE has pioneered new methods of data quality control and archiving, which will be used in future programmes such as CLIVAR (see the article by Legler and Crease, pp 19-20). In addition, WOCE has encouraged continued research into model design and development, resulting in significant strides in our modelling capabilities during the last decade (Griffies et al 2000 and the article by Wood and Killworth, page 10).

Despite the generally optimistic tone of this article, it must be admitted that not all technology developments made in WOCE were successful or widely implemented. For the WHP, there was a major thrust to build a novel, streamlined sampler that would replace the bulky CTD/multisampler packages that could only be raised and lowered at speeds of typically 1m/s or less and thus reduce the time needed to complete an ocean section (see figure 1). Both cost and technological problems prevented its completion. Similarly a free fall 'fast fish' for CTD observations alone was developed and used but not widely adopted, because of its inability to collect discrete water samples for salinity corrections (Figure 2). However, the technological improvements brought about within WOCE have given us much new understanding of how the ocean varies at all scales, and will be widely used in continuing and new programmes such as CLIVAR and GOOS.

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Lessons learned: Data Management during WOCE

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David M. Legler, DPC co-Chair, US CLIVAR Office, Washington, DC. USA legler@usclivar.org

It is 20 years since WOCE formally got underway with the establishment of the Scientific Steering Group and almost as long since questions of data management started to be discussed. CD readers had yet to appear and the World Wide Web was still a decade away. Much of the ocean observational data was still routinely held by investigators and only informally exchanged within the community. WOCE pioneered the management of physical ocean data for the greater purpose of addressing key scientific questions regarding the role of the oceans in climate. The occasion of the imminent appearance of the final WOCE DVD set is a useful time to reflect on lessons learned during the design and implementation of the WOCE data system.

Recognising the critical need for management of data

It was crucial to the outcome of the Experiment that the Scientific Steering Group was prepared from the start to give attention to and support planning for data assembly and distribution: Such matters nearly always figured on the agenda of the biennial meetings. Accordingly, in the early stages of WOCE, data management planning went hand in hand with the science planning as evidenced by the extensive cross referencing between the Science Plan and Implementation Plan in which the data gathering (sea-going and satellite), were linked to the scientific objectives and the data assembly. The preparation of these documents provided a strong discipline on the execution of the experiment. Moreover, WOCE, by promoting, at an early stage, guidelines on data sharing, encouraged the more rapid sharing of data between individual scientists. The published guidelines were perhaps rather more stringent than many would care for, but they have contributed to the present day willingness to make data available widely at an early stage. This submission of data as soon as it was ready prevented the catastrophic loss or degradation of these data. Delays in providing access to data contributed to some loss of potentially valuable data during WOCE.

Establishing a distributed data framework: co-locating data centres and science experts

WOCE established a central information unit (the DIU) along with a distributed Data Assembly Centre (DAC) network among science groups to assemble, check, and disseminate observational data and metadata as well as provide for a means of determining what data from WOCE were taken and where they reside. Mechanisms for regular communication amongst the centres, oversight and review of progress of the data system towards WOCE goals, and commonly shared objectives and a vision for the WOCE data system produced an esprit-de-corps that focused the distributed centre system elements towards unifying targets.

This distributed and co-location model is now accepted as an excellent mechanism for achieving scientific quality. The close links between those exercising the observational data and those checking the data were critical for identifying suspect data; advancing the quality and scope of the metadata; and instituting refined reporting standards. Some of the most successful groups were those with additional experience in information management. There were disappointingly few operational DACs outside the USA.

Another part of the WOCE plan involved the nomination of

Special Analysis Centres (SAC)-science groups, which would carry out a limited set of standard syntheses on the datasets for the benefit of the WOCE community as a whole. Mostly this did not happen. There was at the time a belief that analysis and synthesis should come within the ordinary scientific funding mechanism, and was not something to be funded independently across a range of science projects.

Addressing WOCE objectives – the need for integrated products

The transition from a Data Management Committee (DMC) to a Data Products Committee (DPC) in mid-term with the emphasis on synthesis was important in principle. The intention was to shift the emphasis in the committee from the scientists at the DACS to those addressing the basic WOCE goals. In retrospect, this would have been a better time rather than early in the experiment to press for the SAC- like activities. Stronger synthesis activities might have developed earlier and avoided some of the rush at the end of the programme, but would have been difficult without the more substantially complete WOCE data set available today. The remit of the Atlas groups, though not actually a DPC activity could be regarded as a SAC-like activity.

Integration of the data sets in response to the requirements of the Science Plan is likely to be an important and major product of the data management. The definition of requirements for integration came relatively late in the programme. Implementation became the responsibility of DACs, which were initially responsible in their mission for assembly and, in collaboration with the PIs, quality control. In retrospect, it may have been better to have one group carry out the integration of the data from the individual DACs as a separate activity leaving the DACs to their job of assembly and quality control functions. The skills and knowledge required for this work are significantly different from those required of the DACs and perhaps more suited to those found, though not exclusively, in national data centres in a number of countries.

The integration of data within dynamic frameworks such as data assimilation systems holds great promise for providing three and four-dimensional products that synthesise (subject to the constraining model dynamics) multiple streams of data.

These needs were recognised by WOCE and indeed were embodied in the general statement of Goal 1 but, given their elaboration (AIMS) only late in the Experiment, their impact on data management was general rather than specific.

We were asked specifically to bring out in this article our thoughts of the "could do better" sort as well as the successes. We believe the success is obvious in the production and content of the WOCE DVDs. They contain between 90 and 100% of the data gathered during WOCE by scientists from around 30 countries, the great majority of it quality controlled by scientists involved in the programme. There will inevitably be errors and omissions on the DVDs, which we would expect to be corrected and added to the planned WOCE archive on-line at the World Data Center-Oceanography, Silver Spring, Maryland at the US NODC.

As the ocean observing system matures into a sustained system, new measurement technologies emerge, and follow-on research programmes (such as CLIVAR) spin-up, the importance of scientific input, emphasis, and support, as well as the implemented coordination of data activities remain as critical challenges that must be vigorously pursued.

The Legacy of WOCE: The WOCE Global Data V3.0 on DVDs

In November 2002 the WOCE Data Products Committee will publish the third and final version of the WOCE Global Data on disk. A superb data resource, the DVDs will contain all the data submitted to the WOCE data system (more than 90% of all data collected in the WOCE field programme).

Highlights of the data include:

- Satellite and *in situ* observations of surface-to-bottom ocean temperature.
- Deep ocean measurements of salinity, nutrients, oxygen, carbon and tracers.
- Direct current measurements from ships, moorings, surface drifters and subsurface floats.
- Sea surface winds from satellites and ship observations.
- Sea level data from satellites and tide gauges.

Accompanying the data are:

- Full documentation for every data set.
- Scientific Quality Control information for every data set.
- Additional scientific products including air-sea flux fields.
- eWOCE: an electronic atlas of WOCE data, including plotting tools.

On each DVD will be a search and retrieval tool to allow you to find the data that you need from the diverse WOCE data streams (e.g. temperature data from a particular area and time frame from ALL temperature sensors).

Free copies of the DVDs will automatically be sent to everyone who received an earlier version of WOCE Global Data on CDs, and will be presented to attendees of the Final WOCE Conference in November 2002. If you would like to receive a free copy of the "ultimate" WOCE data set, please send your name, affiliation, email and full postal address to:

Mrs Jean Haynes, WOCE International Project Office, Southampton Oceanography Centre, European Way, Southampton, SO14 3ZH, UK
jchy@soc.soton.ac.uk, Fax: +44 (0)23 8059 6204

From WOCE to CLIVAR: A Legacy and the Future

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Just as TOGA (the Tropical Ocean Global Atmosphere, 1985-1994) left a legacy upon which the CLIVAR programme was established, so too has WOCE established a solid foundation to study the ocean's role in climate. During the TOGA decade, routine observations of the air-sea interface and upper ocean thermal structure in the tropical Pacific Ocean were provided in real time by the TAO array. These mooring observations have since been sustained in the Pacific and extended to the Atlantic. Coupled ocean-atmosphere prediction models were established and implemented at many of the world's major prediction centers. Ocean data assimilation proved to be a key element to the initialisation of seasonal to interannual climate forecast systems. In addition, the overall approach to climate science evolved during TOGA. Prior to TOGA, in the early to mid-1980s, oceanographers and meteorologists were often in separate and distinct communities. As part of TOGA, these communities came together to form a new breed of climate scientist realising that there are modes of variability that occur in the coupled ocean-atmosphere system that do not exist in the uncoupled ocean or atmosphere. In a similar manner, WOCE has left a significant imprint on our knowledge of the global oceans, changes in the technology we use as oceanographers, and overall changes to our scientific method.

During WOCE, a global perspective for the temporal variability of the world's oceans, from top to bottom, was realised. The notion of a steady general ocean circulation or a "snapshot" approach to observing the ocean was refuted by evidence from repeat sections of the WOCE global hydrographic survey. This survey established a baseline to assess changes in time and evaluate anthropogenic effects on the global ocean circulation. In partnership with JGOFS, a CO_2 and tracer chemistry survey was enabled. Regional process studies and focused observational campaigns improved our knowledge of the Southern Ocean, deep water formation in the GIN and Labrador Seas, and refinements to our understanding of ocean mixing, the global thermohaline circulation and the meridional transport of heat from equator to pole.

Advances in ocean technology played a major role in permitting a truly global ocean perspective. Continuous observations of global sea surface height were provided by the TOPEX/Poseidon and ERS radar altimeters. This data stream seems assured with the Jason-1 and related follow-on missions. Active and passive microwave satellite sensors provide all-weather retrievals of the ocean surface wind velocity. Improved instrumentation and calibration has led to refinements in air-sea flux capabilities from both ship and mooring based platforms. Within the ocean, developments in float technology during WOCE led to the Argo programme and the concept of a global deployment of profiling floats. Experimental devices such as gliders have the potential for performing repeat sections in historically difficult to observe regions such as western boundary currents. Initiated by the WOCE Community Modeling Effort and fueled by advances in computer technology, global ocean models now exist which can resolve energetic boundary currents, associated instability processes, and provide a dynamically consistent description of many observed aspects of the ocean circulation.

WOCE also changed the way we look at the ocean and work as an oceanographic community. The idea of an ocean synthesis in which *in situ* observations and/or remotely sensed observations are brought together with inverse methods or data assimilation methodologies such as the adjoint or Kalman filter, has changed our approach to global oceanography. The prospect of global temperature and salinity profiles from Argo underpinning radar altimeter observations together with the prospect of absolute dynamic topography from GRACE and high-resolution ocean models have all contributed to the concept of a Global Ocean Data Assimilation Experiment (GODAE). Real-time global ocean observations have ushered in the possibility of operational oceanography on a global scale. We are now at the point when the oceanographic equivalent of a World Weather Watch is not a folly limited by logistics, but is in fact on the verge of reality.

Although WOCE has laid down this solid foundation, it is incumbent upon us to build on the successes of WOCE, address any shortcomings that may have taken place, and advance our understanding of the ocean's role in climate. At the conclusion of WOCE, and now that CLIVAR is well underway, there exist many questions and issues, both scientific and programmatic, that need our attention as we look to the future. For example, what is the role of the extra-tropical oceans in climate change and climate predictability? What are the time and space scales by which the ocean feeds back to the atmosphere? What is the fate of the thermohaline circulation in a warmer world? What sort of sampling strategy (both space and time) is needed, or for that matter is possible, for the deep ocean below 1000m? How can we build upon the heritage of the WOCE/JGOFS collaboration in support of the CLIVAR and carbon communities? As an oceanographic community or for that matter climate community, are we positioned to take full advantage of Argo observations? How can we build upon the success of atmospheric reanalyses and the efforts of GODAE to implement an equivalent programme for regular, periodic, and consistent (re)analyses of the ocean climate spanning tens of years? Sea surface salinity observations may become possible from experimental satellite missions like Aquarius. However, what are the next generation of ocean observations that we require from space? What are the key oceanographic processes or ocean metrics that need to be included or diagnosed in coupled ocean-atmosphere models of climate change? Needless to say, WOCE has provided a much needed basis by which we can make progress on many of these questions. The transition to CLIVAR (now the only WCRP programme focused on the global ocean) has begun in earnest and our understanding of the coupled climate system is clearly benefitting as a result.

Cost-benefit Analysis of WOCE

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Introduction

With WOCE coming to an end one of the questions that funding agencies might ask is: Was WOCE worthwhile in terms of its economic return and societal impact? Trying to answer this question involves measuring the benefits generated against the project costs. This kind of evaluation is often used in both the public and private sector and is known as Cost-benefit Analysis (CBA). In the case of WOCE this is not an easy matter. It requires a major effort to gather the information on expenditure and to translate the benefits into monetary terms. While not overcoming all these difficulties, this study attempts to build a simple model for a cost-benefit analysis of WOCE.

WOCE is almost finished and its costs can be estimated with some degree of confidence. Although WOCE had broad objectives (and hence no finite, direct beneficiary), ultimately the benefits will come from the future value of climate predictions and ocean monitoring along with any societal and additional scientific benefits (which are not easily quantifiable).

This study has to make several assumptions in order to reach a tractable approach, while ensuring an objective assessment of the economic value of WOCE. It therefore follows the model proposed by Sassone and Weiher (1997). Determining whether WOCE was a sound use of public resources will help funding agencies that have budget responsibility in this area to assess whether additional funding should be allocated for climate studies and forecasting efforts at both the national and international levels.

WOCE Costs

WOCE was funded by the national agencies of each participating country (about 30 in total). Among these only a few have been able to provide a detailed budget of their WOCE expenditures. Others could only provide an estimate of their WOCE costs. The difficulties in obtaining a reasonable budget were mainly due to:

- No accounting procedure in place in some countries (particularly at the beginning of WOCE)
- Inconsistent accounting procedures among the funding agencies
- Inconsistent accounting procedures within the same agency but for different time periods due to changes of personnel
- The variety of funding sources: Block funding vs competitive proposals

It was therefore necessary to develop estimation criteria based on the information provided directly by the countries.

The core expenditure of WOCE is most readily identified in the project's observational phase. The fieldwork carried out has been well documented by the WOCE International Project Office and Data Information Unit (www.woce.org). The WOCE fieldwork costs have been derived using certain assumptions (which are beyond the scope of this article). This is an exercise fraught with difficulties because of the different costs of particular activities in each country. For this reason all costs have been calculated based on U.S. rates, using the known costs of the U.S. Indian Ocean expedition, which provides the best cost analysis for hydrographic data gathering.

The costs for the planning phase and AIMS phase has been added to the estimated fieldwork costs only for the countries that could provide those figures. Unfortunately no documentation is yet available for inferring the total costs of these two phases with any confidence. However the countries that did provide those costs are those that contributed more to WOCE fieldwork and therefore we can say with some confidence that the total cost omitted is within the statistical error of the total costs estimated. Given the nature of the uncertainties, the error associated with the total WOCE cost is also very difficult to estimate. Arbitrarily we assigned a 10% error to each variable. All the costs are detailed in the Table 1.

The total estimated cost of WOCE is about $2.2 billion. Satellite expenditure accounts for around 73% of this, while the US contribution is the highest among all the countries with 32% of the total. Additional (to those mentioned above) uncertainties in the actual cost of WOCE are due to the fact that WOCE has not yet ended and therefore the WOCE total cost is based upon the up-to-now expenditures.

Potential Benefits of WOCE

"The World Ocean Circulation Experiment is aiming at a scientific problem the resolution of which will have great benefits for mankind, for the rich and the poor, and for those living not only on the water's edge but also in the interior of continents far from the ocean." (from the Introduction to the Scientific Plan for the World Ocean Circulation Experiment WCRP, 1986).

WOCE has collected a global data set of unprecedented accuracy and spatial resolution and has integrated these measurements into mathematical models. This has given a much-improved understanding of the oceans and a better definition of the role of the ocean in the climate system. This will ultimately improve interannual to decadal climate forecasts, reduce uncertainty in the prediction of climate change associated to anthropogenic emissions, and improve ocean statistics and basic research and technology, thereby producing benefits for people and business throughout the world economy.

Estimating the overall economic benefits from WOCE is hindered by the lack of direct estimates of the value of WOCE achievements and projected applications. Unfortunately no analysis is available that identifies direct benefits accruing from having a greater understanding of oceanographic features and assigns a monetary value to these benefits. However, even without precise information, much can be said about the likely magnitude of WOCE economic benefits.

On timescales of years, climate variability forecasts are valuable to agriculture, fisheries, energy management, coastal protection, transportation and facilities planning. One recent study (Solow et al., 1998) found that by incorporating NOAA's ENSO (El Niño/Southern Oscillation) forecasts into planting decisions, farmers in the US could increase agricultural output and produce benefits to the US economy of up to $300M per year. Similarly to ENSO, the North Atlantic Oscillation (NAO) has dramatic effects on agriculture in Europe, as well as on the other climate-sensitive industrial sectors, but its predictability is still poor. WOCE science is contributing to understanding the NAO phenomenon, thus we would expect significantly better long-term weather forecasts hence proven substantial benefits to agriculture in Europe.

An obvious WOCE legacy is its data sets. They revealed fundamental processes relevant to global climate change and they form a high quality baseline against which to assess future changes. Estimates of ocean heat and freshwater transports, global air-sea heat and momentum fluxes and the sequestration of atmospheric carbon by oceanic processes will be improved because of WOCE. In addition, some WOCE data, such as sea-level measurements, include the effects of climate change, so will allow us to better predict the magnitude of these effects. Several studies argue that global climate change may cause the ocean to spawn more frequent extreme events, e.g. persistent and stronger ENSO phases (Timmermann et al. 1999), which influence economic activity on land. There are also worries that global warming could influence the thermohaline circulation and possibly cause it to shut down entirely, causing an abrupt decrease of temperatures in North Western Europe. These are just two examples where the value of the information on ocean processes and forecasts, which WOCE can provide, would be very high.

Table 1: Costs of WOCE (in $Millions) Estimated 01/03/2001

Country	**WHP-OT**	**WHP-RH**	**Drifters**	**Floats**	**XBT**	**Moorings**	**Sea Level**	**Satellites**	**Modelling, Process Study & Air-Sea Flux**	**Data Management**	**Tech. Dev. & Coordination**	**Total**
Argentina		1.64	0.04		0.01		0.52				0.50	2.71
Australia	4.68	11.39	0.21		2.72	8.60	2.86			3.25	0.50	34.21
Brazil		0.58	0.13				0.78				0.50	1.99
Canada	3.22	14.73	0.36	0.09	0.08	3.35	0.78			3.25	1.50	27.36
Chile		1.88					2.08				0.50	4.46
China		3.58	1.00		0.24	2.05					0.50	7.37
Finland		0.79				0.10		55.00			0.50	56.39
France	13.09	9.41	1.34	1.59	3.64	2.85	1.82	264.00		3.25	0.50	301.49
Germany	11.85	13.89	0.78	2.10	1.16	25.50		55.00		3.25	0.50	114.03
Iceland		0.64	0.28								0.50	1.42
India			0.35								0.50	0.85
Japan	9.11	15.59	1.08	0.22	1.10	2.00	3.64	201.50		3.25	0.50	237.99
Korea			0.13				0.26				0.50	0.89
Netherlands		2.88	0.04		0.05			55.00			0.50	58.47
New Zealand		1.44	0.11			2.60	1.04				0.50	5.69
Portugal			0.15	0.24		0.60	0.26	55.00			0.50	56.75
Russia	3.41	0.87			0.08		0.26				0.50	5.12
South Africa		1.02	0.51	0.35			1.04				0.50	3.42
Spain	1.57	1.95		0.20		0.80	0.26	55.00			0.50	60.28
UK	6.22	4.15	0.14	0.07	0.09	8.80	2.60	55.00		3.25	0.50	80.82
USA	72.83	15.42	15.20	17.08	12.09	34.60	16.38	410.50	73.78	29.25	15.71	712.84
others		2.98	0.97		0.04		5.46	430.00			4.50	443.95
Total	**125.98**	**104.83**	**22.82**	**21.94**	**21.30**	**91.85**	**40.04**	**1636.00**	**73.78**	**48.75**	**31.21**	**2218.50**

WOCE contributed to basic research in the field of oceanography and climatology. The WOCE bibliography already contains around 5700 publications, of which 1700 are refereed publications directly resulting from WOCE research. Advances in ocean modelling, in particular, were very pronounced and will feed into future climate variability and global change research. WOCE also provided substantial progress in various technologies that aimed to provide cost effective high quality ocean measurements. These include satellites sensors for global synoptic measurements of surface ocean properties and autonomous devices that measure subsurface ocean properties and are particularly useful for taking measurements in hostile conditions. These new technologies are the WOCE legacy to future operational oceanographic programmes. The existence of a direct relationship between Research and Development (R&D) expenditures and social and economic development is widely acknowledged, with many case studies demonstrating this supposition.

Cost-Benefit Model to WOCE evaluation

In this section we attempt to perform a CBA on WOCE by comparing the present value of the benefits and opportunity costs over a period of time that extends back about 15 years and 10 years into the future. The analysis would be retrospective with regard to planning and R&D costs (associated to the observational phase) and prognostic with regard to R&D costs associated with the data analysis and model forecast development. The benefits would largely stem from the value of improved interannual/ decadal climate forecasts. (As previously stated, the value of improved climate forecasts has only recently been considered, and then only in a few regions of the world for certain climate-sensitive sectors.)

Agriculture is the most climate sensitive industry and climate is the primary determinant of agricultural productivity. A recent study by Chi-Chung et al. (2001) quantified the damage to U.S. agricultural economic value (producer income plus consumer expenditures) that would arise from changes in ENSO frequency and strength. The work attempted to estimate the monetary value of a reliable ENSO forecasting system, one that would allow farmers to prepare for future climate conditions ahead of planting. Results indicated that incorporating ENSO information during phase and intensity shifts due to climate change, increases the value of agricultural welfare by about $556 million per year.

Our ability to forecast climate change related ENSO conditions is the result of investments in ocean observing systems and climate research to which WOCE has directly contributed. It is therefore appropriate to use the figures of Chi-Chung et al. (2001) as the expected benefits in our CBA model for WOCE. It is also the only work we could identify which has attempted to quantify, at the national level and taking general equilibrium considerations into account, the economic value of a climate variability prediction. At this point it is important to underline that by following the method of Chi-Chung et al. (2001) we are ignoring the benefits in economic sectors other than agriculture and in countries other than the USA. Hence we are understating the actual WOCE benefits to a substantial extent. Also, by ignoring any economic benefits arising from the forecast of other climatic events (like NAO, hurricane intensification, climate change etc.) we are further understating total benefits. Thus, we believe it is appropriate to interpret our results as lower band estimates of the WOCE programme.

All the values of costs, benefits and related calculations are organised in a spreadsheet shown in Table 2. We perform our analysis anchored in the year 2000, as the time index clearly indicates in the column A, while the column B shows the corresponding years relevant to the analysis. The WOCE related costs incurred in each year up to and including 2000 are presented in column C. In column D we include an estimate of the expected annual cost of WOCE after 2000 based on the future activities detailed at the last meetings of the WOCE Scientific Steering Group.

Although the costs are adjusted for inflation, they are not adjusted to account for the present value of those historical costs. The adjustment for present value is done through the Internal Rate of Return (IRR). A way of interpreting the IRR is as the discount rate which, if used to calculated the Net Present Value (NPV) of the investment, would result in a value of zero $. A project's calculated IRR should be compared with the opportunity cost of that investment (the rate of return that could be earned in the next best investment), currently organisations like the US Office of Management and Budget and European Union suggest a real value of 7% as the appropriate hurdle (IRR) rate.

For the purpose of this analysis we built into the CBA model a "forecast acceptance curve" because there is likely to be an incomplete acceptance by farmers of ENSO forecasts (at least initially). The particular curve, illustrated in Table 2, embodies the assumption that acceptance starts off at 50% level, and builds to a maximum of 90% over a 10-year period (column H).

Finally, column J shows the annual net benefits of the WOCE investment (benefit-costs). The Internal Rate of Return (IRR) is calculated from the values in this column, which show the annual flows of resources either consumed or generated, by WOCE.

In order to deal with uncertainties we performed a simple sensitivity analysis in its simplest applied version, which is to vary one variable at each time and calculate the corresponding values of IRR. In the sensitivity analysis we deal with the uncertainties of three variables: The rate of acceptance of ENSO forecasts by the agricultural sector, the cost of the WOCE project, and the future time horizon. By varying these three parameters, 12 scenarios are generated. The calculated IRR for the 12 scenarios ranges from 2% to 23%. The sensitivity analysis confirms that

Table 2. Cost-Benefit Analysis Worksheet

A Time Index	B Fiscal Year	C WOCE Costs	D Estimated annual post-2000 costs of WOCE (in 1995 $millions)	E Implicit Price Deflector for federal nondefence purchases	F Factor to Adjust Costs 1995 $	G Total pre-2000 Costs (in 1995 $millions)	H Acceptance curve	I Estimated annual benefits (in 1995 $millions)	J Estimated annual net benefit (in 1995 $millions)
-15	1985	19.87		71.44	1.37	27.23			
-14	1986	19.87		73.06	1.34	26.62			
-13	1987	19.87		74.58	1.31	26.08			
-12	1988	19.87		76.85	1.27	25.31			
-11	1989	19.87		79.27	1.24	24.54			
-10	1990	27.65		81.95	1.19	33.03			
-9	1991	441.93		86.07	1.14	502.67			
-8	1992	452.27		87.71	1.12	504.82			
-7	1993	56.48		91.58	1.07	60.38			
-6	1994	57.07		94.55	1.04	59.09			
-5	1995	459.22		97.90	1.00	459.22			
-4	1996	455.46		100.00	0.98	445.90			
-3	1997	55.91		102.06	0.96	53.63			
-2	1998	43.71		103.41	0.95	41.38			
-1	1999	32.80		106.05	0.92	30.28			
0	2000	36.66		109.21	0.90	32.86			
sum		2218.51				2353.04			-2353.04
1	2001		15				50%	278.0	263.0
2	2002		15				50%	278.0	263.0
3	2003		6				60%	333.6	327.6
4	2004		3				60%	333.6	330.6
5	2005		3				70%	389.2	386.2
6	2006						70%	389.2	389.2
7	2007						80%	444.8	444.8
8	2008						80%	444.8	444.8
9	2009						90%	500.4	500.4
10	2010						90%	500.4	500.4

within the variability of our system, WOCE investments generate future benefits. Given that our analysis is concerned only with benefits generated for the US agricultural sector, it is remarkable that the overall result indicates that WOCE is likely to generate positive dividends much greater than its costs for all countries worldwide in all climate-sensitive sectors.

Conclusions

Overall the cost-benefit analysis performed in this study clearly indicates that the WOCE project was a worthwhile public investment. All the scenarios produced by the sensitive analysis give a positive Internal Rate of Return, with a maximum value of 23%. Our results also suggest that developed countries worldwide have a strong incentive to support the development of global climate observing systems, since the benefits from prediction of climate variability and climate change depend upon the improvement of climate models. Finally, more studies are required of the economic value of climate forecasts. These should be performed for specific economic sectors (agriculture, energy and water resources having the highest priority) and addressed both in so called developing countries and well developed countries where those sectors contribute significantly to the GNP. Funding agencies and organisations should give priority to these studies and enhance their interdisciplinary nature.

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<u>WOCE Final Conference Provisional Programme</u>

San Antonio, Texas 18 - 22 November, 2002

Note that times indicated for presentations include 10 minutes for questions and discussion. Italicised names indicate presenters for which there are multiple authors. Please check the web site for further updates (http://www.WOCE2002.tamu.edu).

Sunday, 17 November 2002
1400-1800 Registration desk open at the Conference Center. Posters may be put up.
1800-1930 Conference Reception — Conference Center

Monday, 18 November 2002
Theme: New global perspectives.
"What were our observational capabilities in 1980? What are they now and how has WOCE helped? What might be our capability in 2010? In 2050?"

Session Chair: **Rana Fine**
0830-0850 Conference opening and Welcome
Welcome on behalf of the WOCE Scientific Steering Group and International Project Office — **John Gould**
Welcome to San Antonio, Texas on behalf of the Conference Steering Committee; Recognition of Conference Sponsors — **Worth D. Nowlin, Jr.**
0850-0920 Why did we do WOCE? — **Carl Wunsch**
0920-1010 Satellite microwave observations of the global ocean — ***Dudley Chelton*** **with Kathryn Kelly**
1010-1040 Coffee

Session Chair: **Kara Lavender**
1040-1130 The inferred three-dimensional velocity field — **Nelson Hogg**
1130-1220 New technologies: Developments during WOCE and what the future might hold — **Uwe Send**
1220-1310 New insights from ocean models — ***Anne-Marie Treguier*** **with Claus Böning**
1310-1430 Lunch
1430-1800 Posters

Session Chair: **Gregory Johnson**
1600-1650 Review talk: The Pacific Ocean — **Lynne Talley**

Tuesday, 19 November 2002
Theme: What are the oceans' roles in property transports and exchanges with the atmosphere?

Session Chair: **Kimio Hanawa**
0800-0850 Ocean transport of heat and freshwater–How good are our estimates? Has WOCE changed the values and uncertainties? — **Alexandre Ganachaud**
0850-0940 Water mass formation–a climate dynamics perspective — **Eli Tziperman and Kevin Speer**
0940-1010 Coffee

Session Chair: **William Jenkins**
1010-1100 Uptake, transport, and storage of carbon by the ocean–implications for the global carbon cycle — **Nicolas Gruber**
1100-1150 Ocean exchanges with the atmosphere–did we learn anything during WOCE? — **Peter Taylor**
1150-1240 Global synthesis. How far have we come? How far might we get? — **Detlef Stammer**
1240-1400 Lunch

Session Chair: **Lisa Beal**
1400-1450 Hydrographic tracers–from description to quantification — **Monika Rhein**
1450-1800 Posters
1600-1650 Review Talk: The Indian Ocean — **Friedrich Schott**

Wednesday, 20 November 2002
Theme: What insights has WOCE produced regarding how the ocean works, and what are the remaining problems?

Session Chair: **Wilco Hazeleger**
0800-0850 Ocean mixing matters! Stirring progress and exciting challenges — **Christopher Garrett**
0850-0940 Boundary currents and interbasin flows. Indicators of the oceans' state? **— Harry Bryden**
0940-1010 Coffee

Session Chair: **Paul Robbins**
1010-1100 Do models of reduced complexity have any useful skill? — **Thomas Stocker**
1100-1150 The ocean mesoscale–Is it important for climate? **— John Marshall**
1150-1240 The co-evolution of oceanic ecosystems and physical circulation — **Paul Falkowski**
1240-1400 Lunch

Session Chair: **Alejandro Orsi**
1400-1450 Water masses–classification, formation, and modification **— Toshio Suga**
1450-1800 Posters
1600-1650 Review Talk: The Southern Ocean — **Steve Rintoul**
1930 Conference Dinner at the *Institute for Texan Cultures*

Thursday, 21 November 2002
Theme: What do we know about the ocean's role in climate, and what are the next main objectives?

Session Chair: **Hiroyasu Hasumi**
0800-0850 Tropical–Intertropical interactions, including ENSO — **Mark Cane**
0850-0940 What do the large-scale modes of extratropical variability imply about memory and predictability? **— David Thompson**
0940-1010 Coffee

Session Chair: **Stephen Griffies**
1010-1100 Sea level rise–can we explain what we measure? — **Anny Cazenave**
1100-1150 The ocean component of coupled climate models–What parameterizations and resolutions are needed and how do they vary with time scale? — **Richard Wood**
1150-1240 How have WOCE observations challenged ocean models? **— Julie McClean**
1240-1400 Lunch

Session Chair: **Herle Mercier**
1400-1800 Posters
1600-1650 Review Talk: The Atlantic Ocean–from the Meteor Expedition through WOCE — **Allyn Clarke**

Friday, 22 November 2002
Theme: Beyond WOCE-Where do we go from here?

Session Chair: **John Church**
0830-0920 Climate stability and instability–transition from flywheel to driver **— Jochem Marotzke**
0920-1010 The Future of Climate Observations in the Global Ocean — ***Dean Roemmich*** **with John Gould, Jim McWilliams, Neville Smith, Detlef Stammer, and Doug Wallace**
1010-1040 Coffee
1040-1105 WOCE, the Oceans, and the WCRP **— Peter Lemke**
1105-1155 After WOCE what are the remaining challenges and how should we set about meeting them? **— Jürgen Willebrand**
1155-1200 Closing Comments and Adjourn

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